A DISCUSSION OF THE H-ALPHA FILAMENTARY NEBULAE AND GALACTIC STRUCTURE IN THE CYGNUS REGION

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Abstract

From a discussion of the galactic structure in Cygnus, the system of filamentary nebulae is found to lie at a distance of roughly 1.5 kpc, in the same region as about half the thermal radio sources in Cygnus X, the supernova remnant near γ Cygni, and the association Cygnus OB2, in the direction of which the X-ray source Cygnus XR-3 is observed. The source of excitation seems likely to have been the pulse of radiation from a supernova explosion, as has been proposed in the case of the Gum Nebula, but continuing excitation by early-type stars in the region of Cygnus X cannot be excluded.

Introduction

The region in Cygnus from $\ell = 70°$ to $90°$, b = $-10°$ to $+10°$, is unusual for the large number of sharp filaments found on either side of the galactic plane (Figure 1). We shall first discuss the location of the filaments with regard to that of other galactic features in this region, and then we shall discuss the question of whether the source of their excitation might have been the pulse of radiation from a supernova explosion such as has been suggested by Brandt et al. (1971) for the Gum Nebula.

I. The Distance to the Filaments and their Relation to Other Features

The galactic structure in the Cygnus region is difficult to untangle. We are looking almost tangentially along a spiral feature containing a large number of dense dust clouds which hide much of the region from us optically. In addition, the velocity-distance relation gives velocities in the range $\pm$ 5 km s^{-1} at $\ell = 80°$ out to a distance of 4 kpc.

Notable features of the region, in addition to the filaments and the dark clouds, include the following objects: i) The complex of thermal radio sources Cygnus X contains many H II regions, a few of which are associated with visible emission nebulae. ii) Several OB associations range in distance from 1 kpc to 2.3 kpc (Alter, Balázs, and Ruprecht 1970). One of these, Cygnus OB2 ($\ell = 80\overset{\circ}{.}1$, b = $+0\overset{\circ}{.}9$), lies at a distance of 1.5 kpc (Schulte 1958) in the direction of the center of Cygnus X and of the system of filamants. iii) The X-ray source Cygnus XR-3 is observed within the projected boundaries of Cygnus OB2 at $\ell = 80^{\circ}\!.0$, $b = +0^{\circ}\!.7$ (Giacconi et al. 1967). Gorenstein, Giacconi, and Gursky (1967) point out that the low-energy attenuation observed in the spectrum of Cygnus XR-3 indicates a column density of neutral hydrogen of 3×10^{22} cm^{-2}. Although this could be intrinsic to the source, it could also indicate a distance of a few kiloparsecs (Gursky, Gorenstein, and Giacconi 1967). iv) The supernova remnant near γ Cygni, designated by its galactic coordinates (Wendker 1970) G 78.2 + 1.8, has a diameter of 8 arc min and a flux density S(400 MHz) = 630 flux units (Higgs and Halperin 1968). Using the relation given by Poveda and Woltjer (1968), we estimate its distance as 1.4 kpc; Downes (1971) estimates its distance as 3.4 kpc.

At present the most practical way of obtaining distances to the emission nebulosities in the region is by associating them with dust whose distribution can be estimated from star counts and from measurements of the reddening of early-type stars. According to Miller's (1937) analysis of star counts, the nearby dust clouds in this direction begin about 600 pc from the sun. The most extensive observations of the interstellar reddening of stars in this region are those of Ikhsanov (1959), who gives curves of absorption against distance for eight regions in a 6° square area NW of γ Cygni, an area where many filaments are seen. His curves appear to be reliable out to distances of 1.5 to 2 kpc. He confirms Miller's results, and in addition he finds that the more distant dark clouds between $\ell = 78^{\circ}$ and 85° set in at about 1 kpc. These results are further confirmed by Neckel's (1967) analysis of existing photoelectric measurements and MK spectroscopic classifications. Neckel's results show that significant absorption in otherwise clear regions sets in between 2 and 3 kpc.

a) Filaments

The Palomar Observatory Sky Survey shows numerous sharp filaments from $\ell = 75^{\circ}$ to 87° between $b = +2^{\circ}$ and $+7^{\circ}$. Some fainter filaments are found between $\ell = 77^{\circ}$ and 83°, $b = -3^{\circ}$ to -8°. Filaments of this nature are uncommon on the Sky Survey plates. Van den Bergh's (1960) search of the Sky Survey yielded nine examples of this type of filaments, including this region; the remaining eight are well-known supernova remnants. Thus it is highly likely that the Cygnus filaments have been produced by a single event. Although there is no well-defined geometric center of these filaments, a circle of radius 8.5 degrees centered at $\ell = 80^{\circ}$, $b = +1^{\circ}$, includes most of them. Morgan, Strömgren, and Johnson (1955) noted that the filaments north of the galactic plane seem oriented perpendicularly to the line toward Cygnus OB2; this has been confirmed quantitatively by Dickel, Wendker, and Bieritz (1970). The association Cygnus OB4 ($\ell = 82^{\circ}\!.5$, $b = -7^{\circ}\!.3$) lies in the direction of some of the filaments south of the galactic plane, and a weak X-ray source, Cygnus XR-4, has been reported in this region (Giacconi et al. 1967).

In estimating a distance to the filaments, we first note, as has been remarked by Ikhsanov (1960), that because an insignificant amount of radio continuum emission is seen in their direction, the filaments are unlikely to be intrinsically very bright structures that are obscured by dust. This is confirmed by comparison of the filaments appearing in the list of H-alpha sources by Dickel, Wendker, and Bieritz (1969) and the list of discrete radio sources in the same region by Wendker (1970). We identify 86 of the H-alpha sources of Dickel et al. with filaments; nine of these appear in Wendker's list. However, since their flux is very low, the uncertainty in the background corrections makes a determination of the reddening meaningless.

In the area of the sky that he surveyed, Ikhsanov's (1959) regions 1 and 7 contain most of the bright filaments. The filaments appear to be obscured or in some cases partially obscured by dark clouds in regions 2, 6, and 8; essentially no filaments are observed in regions 3, 4, and 5. According to the results of both Ikhsanov and Neckel (1967), in the regions where filaments are obscured or absent, significant absorption amounting to several magnitudes sets in at distances around 1 kpc. By contrast, in regions 1 and 7, which contain most of the bright filaments, there is no significant absorption before a distance of 1.6 kpc; however, by 2.5 kpc significant absorption has set in. The small number of stars observed beyond 1.6 kpc does not allow the onset of absorption to be defined more accurately. We tentatively conclude that the filaments lie in the range 1 to 2 kpc, and we shall adopt a mean distance 1.5 kpc.

b) Thermal Radio Sources

A detailed radio map of Cygnus X (Wendker 1970) shows 76 discrete thermal radio sources in this area, which are probably all more or less obscured H II regions. By comparing the H-alpha radiation and the radio continuum flux, Dickel et al. (1969) estimated the absorption in front of these regions and then determined distances from Ikhsanov's (1959) curves of absorption against distance. Only 20 percent of the H II regions are more distant than 4 kpc. Most of them are found in the interval from 1 kpc to 2.5 kpc; slightly more than half are in the range 1.2 to 1.8 kpc.

In addition to these discrete sources, Wendker (1970) finds an unresolved background thermal source containing about half the total flux of Cygnus X lying within an area of size $5\overset{\circ}{.}6 \times 3\overset{\circ}{.}5$ (at the $T_b = 1°K$ level) covering essentially the same area where the discrete thermal sources are found.

II. The Source of Excitation of the Filaments

We now turn to a discussion of the objects observed near the location of the filaments to consider the possibilities for their excitation. At the distance 1.5 kpc near $\ell = 80°$, $b = +1°$, we find the association Cygnus OB2, more than half the discrete radio sources in the Cygnus X complex, and the supernova remnant G 78.2 + 1.8. The distance of Cygnus XR-3 is uncertain, but it too could be at this same distance. We shall also consider the suggestion of van den Bergh (1960) that the filaments are themselves a supernova remnant similar to the Cygnus Loop.

a) The State of the Filamants

We consider two possibilities for the state of excitation of the filaments: i) steady state, in which the flux of Lyman continuum photons is proportional to the product of the densities of ions and electrons, and ii) ionization by a radiant pulse, in which the total energy of radiation above the Lyman limit, in terms of 15-eV photons, is equal to the number of electrons.

No pulsars have as yet been detected in the region of the filaments in Cygnus (Maran and Modali 1970). Therefore we have relied on the H-alpha emission measurements of Dickel et al. (1969) to obtain the parameters listed in Table 1. In order to calculate the r.m.s. electron density $\langle n_e^2 \rangle^{1/2}$ for the filaments we need to know the thickness L in the line of sight. We have considered two cases: i) "sheets" seen edge-on, for which L has been taken to be the larger dimension, and ii) "cylinders", for which L has been taken to be the smaller dimension. We have adopted the electron temperature $T_e = 6000$ °K used by Dickel et al. (1969), which can be considered reasonable for case i), and we note the dependence of the resulting energy in case ii) as $T_e^{0.425}$ (Seaton 1959). We have expressed the ionizing flux for case i) in terms of the ionization parameter,

$$U = [(3/4\pi) \int n_e^2 \, dV]^{1/3}$$

where the integral is taken over the ionized region, and in terms of O5 stars, for which we have adopted an effective temperature of 49,500 °K (Hjellming 1968a) and an ionization parameter $U = 74$ pc cm^{-2} (Hjellming 1968b).

The number of filaments seen is strongly influenced by obscuration. In order to estimate the total number of filaments we have chosen a sector of angle 60° from position angle 310° to 10° centered on $\ell = 80\overset{\circ}{.}0$, $b = +0\overset{\circ}{.}7$, as being a typical unobscured region. No filaments are seen closer than 2° to this center because of the foreground dust clouds. In the unobscured region there are 71 sources

Table 1
Parameters of extended emission regions in Cygnus

Type of Object	Number of Objects	Total Area (deg^2)	Total Volume[3] (cm^3)	Total Flux	Average Emission Measure ($pc\ cm^{-6}$)	$\langle n_e^2 \rangle^{1/2}$ [6]	Total Electrons	Mass ($M_\odot$)	Ionization Parameter ($pc\ cm^{-2}$)	Energy Required for Ionization	
										(erg)[7]	(O5 stars)[8]
Filaments											
(observed)	44 +	3.1	–	2.6[4]	500	–	–	–	69	–	0.8
"sheets"	42 [1]	–	9.6×10^{59}		–	4.0	3.9×10^{60}	3.2×10^3	–	1.6×10^{50}	–
"cylinders"	–	–	2.6×10^{59}		–	8.2	2.1×10^{60}	1.7×10^3	–	8.8×10^{48}	–
Filaments											
(estimated)	430	15.5	–	13.0[4]	500	–	–	–	118	–	4.0
"sheets"	–	–	4.8×10^{60}	–	–	4.0	2.0×10^{61}	1.6×10^4	–	8.0×10^{50}	–
"cylinders"	–	–	1.3×10^{60}	–	–	8.2	1.1×10^{61}	8.5×10^3	–	4.4×10^{49}	–
H II Regions	66	8.8	2.0×10^{60}	2060[5]	7050	21.0	4.2×10^{61}	3.5×10^3	217	–	25
Thermal Background	1	40.4[2]	1.1×10^{61}	2990[5]	2260	2.9	3.2×10^{61}	2.7×10^4	245	–	36

(1) Dickel et al. (1969) list 42 sources for which no H-alpha flux is given. We have arbitrarily assumed 0.1 (10^{-4} cgs).
(2) Area observed by Wendker (1970) and appropriate for his total flux of 2990 for unresolved and "unaccounted for" H II emission.
(3) Distance assumed to be 1.5 kpc.
(4) $S(H\alpha)$ 10^{-14} W m^{-2} (flux).
(5) S(2695 MHz) 10^{-26} W m^{-2} Hz^{-1} (flux density).
(6) Calculated as uniform sphere.
(7) Calculated on assumption of one 15-eV photon per electron.
(8) Flux necessary to sustain ionization based on ionization parameter of 74 pc cm^{-2} for an O5 star.

from the list of Dickel et al. (1969) that we identify as filaments. Within a circle of radius 8°.5 we estimate there are about six times this number of filaments, or about 430 in all. The parameters in Table 1 for 86 observed filaments are then multiplied by a factor 5 to refer to the expected total number of filaments.

b) Cygnus OB2 and Cygnus X

We have used Wendker's (1970) observations at 2695 MHz to derive the size and radio flux from the H II regions in Cygnus X. We have examined his map and have summed all the 66 discrete thermal sources not associated with visible filaments. The parameters for the sum of these sources are given in Table 1. According to Dickel et al. (1969) slightly more than half of these sources are near the distance 1.5 kpc. The results for the unresolved thermal background are also taken from Wendker (1970). Although the distance distribution of this source is unknown, from its location and extent we have considered it likely that it is largely concentrated in the region near 1.5 kpc where most of the discrete sources are found and near a possible source of excitation, Cygnus OB2.

As given in Table 1, the value of U for the discrete sources is 217 pc cm^{-2} and that for the thermal background is 245 pc cm^{-2}. These have been calculated using the relations given by Hjellming (1968a) for mean temperature 6000 °K, frequency 2695 MHz, and distance 1.5 kpc. Véron (1965) has calculated the ionization parameter of Cygnus OB2 to be 170 pc cm^{-2} for stars with MK spectral types. Using the calibration of Hjellming (1968a,b), this value should be adjusted to 120 pc cm^{-2}. Since Cygnus OB2 has only weak H-alpha and continuum emission in its immediate vicinity (Wendker 1970), it seems a likely source of excitation for much if not all of the thermal background, expecially in view of the incomplete spectral classification for Cygnus OB2, the uncertainties in the calibration of spectral type and effective temperature, and the possible existence of additional obscured members. On the other hand, the discrete thermal sources may well be excited by one or more early-type stars embedded in them and heavily obscured by dust. For instance, on the average, eight O9 V stars (U = 25 pc cm^{-2}) would be required, these being obscured by 6 magnitudes to fall below the limit of discovery (roughly V = 12 mag). Obscuration of this amount certainly occurs in this region. Thus, it seems possible to account for the thermal radiation from the complex by attributing the source of the excitation to obscured early-type stars.

In view of the relatively small flux required to ionize the filaments in the steady-state hypothesis (case i) in addition to that required for the excitation of the whole Cygnus X complex, Cygnus OB2, augmented by other early-type stars and perhaps also by Cygnus XR-3, must be considered a possible source of their excitation.

c) Excitation by a Supernova Explosion

The amount of energy required in case ii), ionization by a pulse of radiation in a brief event, is roughly 10^{50} erg. The only likely source of such an amount of energy is a supernova explosion (Morrison and Sartori 1969).

The appearance of the filaments tends to support this interpretation. It is important to note that the filaments do not resemble in any way Barnard's Loop in Orion; most significantly the filaments contain no "elephant trunk" structures indicative of expansive motion from a long-lasting center of thermal energy. Rather, they have the appearance of intrinsic structures in the interstellar medium such as those seen in the form of dark clouds and reflection nebulae. Brandt et al. (1971) have also suggested a similar interpretation in the case of the Gum Nebula. The filamentary structures in the Gum Nebula are similar in appearance to those in the Cygnus region if they are a factor 10 closer to the sun.

The supernova explosion must have occurred at a time longer than the light travel time but shorter than the recombination time. The light travel time is about 700 years. Spitzer (1968) gives the recombination rate as $2.6 \times 10^{-13}\ n_e^2$ $cm^{-3}\ s^{-1}$ at $T_e = 10^4$ °K, varying as $T_e^{-1/2}$. This corresponds to a recombination time of $1.2 \times 10^5\ n_e^{-2}$ years assuming $T_e = 10^4$ °K. For the filaments the recombination time is 8×10^3 years (sheets), or 1.8×10^3 years (cylinders). However, in the case of ionization by a supernova explosion the temperature could well be much higher and the recombination time longer.

If a supernova flash illuminated the filaments at a time on the order of 10^3 years in the past, we should expect to observe the supernova remnant. We consider the following candidates: i) the supernova remnant G 78.2 + 1.8, ii) the nonthermal radio sources G 78.4 + 2.5 (Wendker 1970) and iii) G 78.6 + 1.0, and iv) the X-ray source Cygnus XR-3. The distance to G 78.2 + 1.8 is 1.4 kpc as derived from Poveda and Woltjer's (1968) relation or 3.4 kpc as given by Downes (1971). Both are probably uncertain by a factor ~ 2, but the distance seems likely to be in the same range of distance as the filaments. By comparison with other supernova remnants in the list of Poveda and Woltjer (1968) its radius of 3 pc at the distance 1.4 kpc would seem to imply an age of roughly 10^3 years. According to Downes (1971), its surface brightness indicates an age of less than 2×10^3 years. These ages are of the same order of magnitude as the light travel time and the recombination times discussed above. The supernova remnants G 78.4 + 2.5 and G 78.6 + 1.0 are both probably more distant than the region containing the filaments (Downes 1971). While observed within the projected area of the Cygnus X complex, these sources are 2°, 2.°5, and 1.°4, respectively, away from the geometric center of the filaments. Cygnus XR-3 is observed in the direction of the filaments, but it has no associated nonthermal radio source; consequently, it is not similar to X-ray sources associated with known supernova remnants (Palmieri et al. 1971). On the basis of our present knowledge we consider G 78.2 + 1.8 to be the most likely candidate of the three.

A third alternative to the above models is collisional ionization by the expanding shell of gas thrown off in a supernova explosion, as has been suggested by van den Bergh (1960). If the filaments represent a late stage in expansion of a supernova remnant, as would be suggested under this hypothesis by the size of the structure, which is ten times that of the largest supernova remnants in the list of Poveda and Woltjer (1968), then their age would be expected to be at least of the order of 10^6 years. Given a rate of supernova explosions in the galaxy of roughly one per 100 years then the entire galactic plane would be expected to be covered with such luminous filaments. This inference does not agree with observations, and thus the model is unattractive.

III. Conclusion

We find the distance of the filaments to lie in the range 1 to 2 kpc from an analysis of their distribution with respect to dust clouds. Thus they lie in the same region as Cygnus OB2, half the radio sources in the Cygnus X complex, probably the supernova remnant G 78.2 + 1.8, and probably Cygnus XR-3. The excitation of the discrete and spread thermal sources seems likely to be supplied by early-type stars. While the excitation of the filaments could also be due to early-type stars, their form suggests that they are more likely to have been ionized by a brief event, such as a radiant pulse from a supernova. It seems unlikely that their ionization is caused by the late stages of expansion of a supernova shell.

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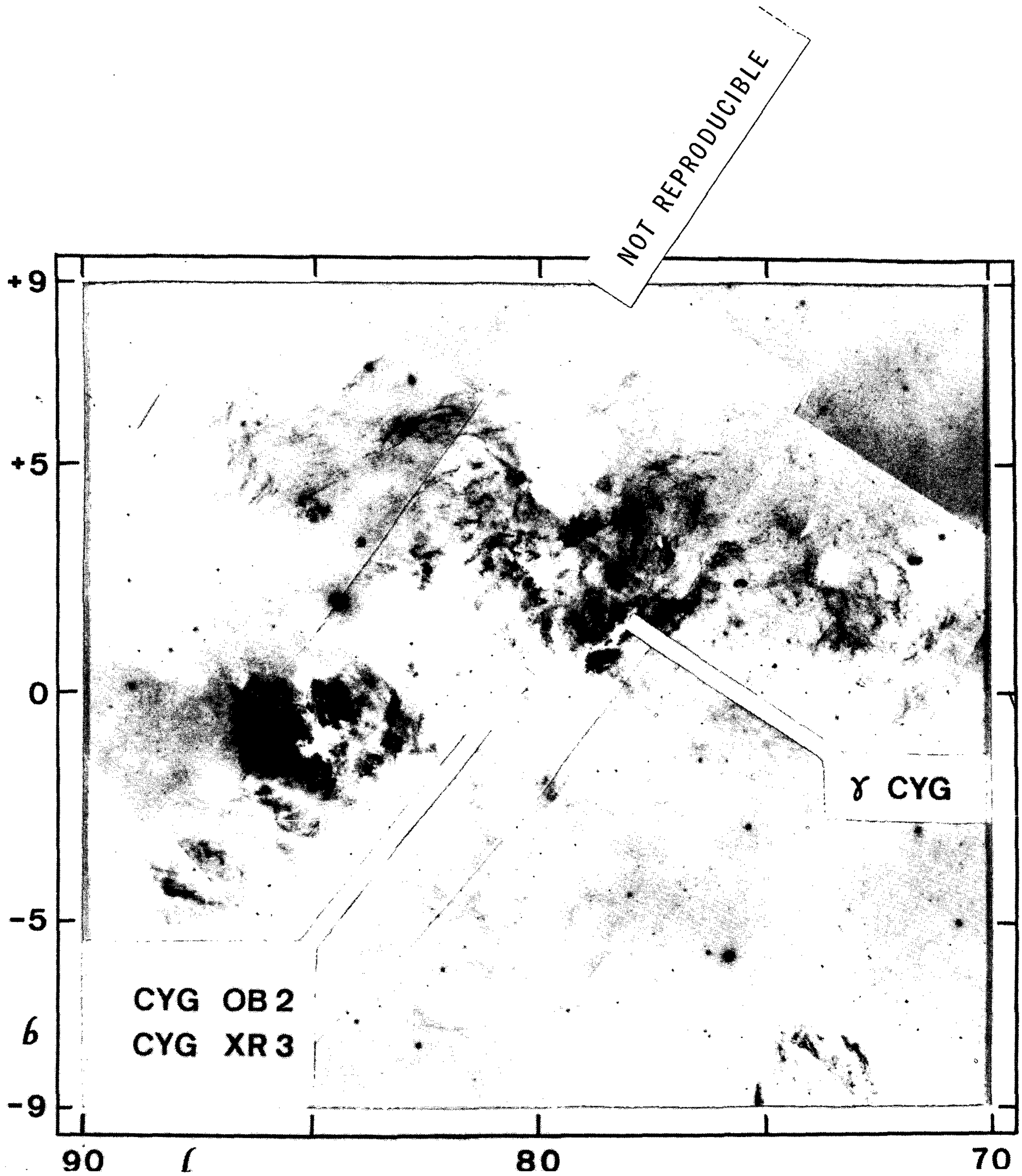

Figure 1. Region of filamentary nebulae in Cygnus (montage of Sky Survey red prints). Copyright by National Geographic Society-Palomar Observatory Sky Survey.